Condition-Based Maintenance Plus and Maintenance Credit Validation

D. D. LE, A. GHOSHAL and E. CUEVAS

ABSTRACT

The Department of Defense (DoD) is currently maintaining the aircraft operability and functionality past the original design intention for many military aircraft. This practice imposes an additional burden on the inspection systems at the DoD logistic centers to ensure the aircraft in operation are airworthy and will be able to complete mission assignments for a specified period of time. Condition-Based Maintenance Plus (CBM^+) has evolved into the U.S. Army leader priority program and becomes a critical technology for the future of the Army to reduce the logistic footprint, maximize the aircraft availability, and increase the component time on wing. To achieve these goals, the Army Research Laboratory (ARL) has initiated the CBM^+ Science and Technology (S&T) Enterprise that spreads across ARL research organizations and supports the Army Research, Development, and Engineering Command CBM^+ initiative in the Army fleet. The CBM^+ S&T Enterprise has three Integrated Product Teams (IPTs), which focus on Hardware and Sensing, Prognostics and Diagnostics, and Data Transfer and Fusion Architecture technologies. The fourth IPT is the Technology Demonstration and Integration.

It has been established that CBM, when joined with the system and/or sub-system prognostic capability (CBM+), could result in tremendous inspection savings, improved aircraft safety and availability, and decreased aircraft downtime and maintenance costs. Under these IPTs, diverse research efforts are being conducted and coordinated by the Technology Focus Working Groups (TFWGs) to combine diagnostics and prognostics capabilities. TFWGs concentrate on many technologies and processes including Structural Health Monitoring (SHM) and Maintenance Credit Validation. One of the challenges for researchers has been the development of the SHM capability that is not only effective and reliable but also relatively low cost and easy to install and maintain while performing the desired function of monitoring DoD systems and sub-systems for loss of structural integrity. SHM methods can be used to monitor the condition of critical structural components and, with other technologies, can determine the structural remaining useful life. As a result, potential maintenance credits, e.g., increased time-between-overhaul or fatigue life adjustment, can be

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The Department of Defense (DoD) is currently maintaining the aircraft operability and functionality past the original design intention for many military aircraft. This practice imposes an additional burden on the inspection systems at the DoD logistic centers to ensure the aircraft in operation are airworthy and will be able to complete mission assignments for a specified period of time. Condition-Based Maintenance Plus (CBM+) has evolved into the U.S. Army leader priority program and becomes a critical technology for the future of the Army to reduce the logistic footprint, maximize the aircraft availability, and increase the component time on wing. To achieve these goals, the Army Research Laboratory (ARL) has initiated the CBM+ Science and Technology (S&T) Enterprise that spreads across ARL research organizations and supports the Army Research, Development, and Engineering Command CBM+ initiative in the Army fleet. The CBM+ S&T Enterprise has three Integrated Product Teams (IPTs), which focus on Hardware and Sensing, Prognostics and Diagnostics, and Data Transfer and Fusion Architecture technologies. The fourth IPT is the Technology Demonstration and Integration. It has been established that CBM, when joined with the system and/or sub-system prognostic capability (CBM+), could result in tremendous inspection savings, improved aircraft safety and availability, and decreased aircraft downtime and maintenance costs. Under these IPTs, diverse research efforts are being conducted and coordinated by the Technology Focus Working Groups (TFWGs) to combine diagnostics and prognostics capabilities. TFWGs concentrate on many technologies and processes including Structural Health Monitoring (SHM) and Maintenance Credit Validation. One of the challenges for researchers has been the development of the SHM capability that is not only effective and reliable but also relatively low cost and easy to install and maintain while performing the desired function of monitoring DoD systems and sub-systems for loss of structural integrity. SHM methods can be used to monitor the condition of critical structural components and, with other technologies, can determine the structural remaining useful life. As a result, potential maintenance credits, e.g., increased time-between-overhaul or fatigue life adjustment, can be understanding of physics of failure of monitored components, direct and/or indirect data that may contain some uncertainties, and methodologies that may be complex and advanced. This paper will document the ARL CBM+ S&T Enterprise strategies in supporting the Army CBM+ implementation goals and developing a process to validate maintenance credits or formulate maintenance-related decisions. Examples of CBM+ actions include the formulation of usage credits and early replacement of monitored parts before using up its component retirement life.

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formulated and proposed. Formulated maintenance credits are based on full understanding of physics of failure of monitored components, direct and/or indirect data that may contain some uncertainties, and methodologies that may be complex and advanced.

This paper will document the ARL CBM$^+$ S&T Enterprise strategies in supporting the Army CBM$^+$ implementation goals and developing a process to validate maintenance credits or formulate maintenance-related decisions. Examples of CBM$^+$ actions include the formulation of usage credits and early replacement of monitored parts before using up its component retirement life.

INTRODUCTION

The U.S. Army is currently operating a fleet of sophisticated equipment and weaponry systems including manned and unmanned as well as autonomous vehicles. Maintaining and sustaining these systems is a monumental task. The Army traditional maintenance program is labor-intensive scheduled and reactive unscheduled maintenance programs [1]. The traditional maintenance practice generates substantial inspection and maintenance man hours and significant downtime of Army equipment or systems, which consequently results in tremendous costs to maintain, operate, and sustain them. As a result, a different maintenance approach, e.g., CBM, developed by the airline industry, was adopted for use in Army equipment and systems.

In the early days, CBM, which has become widespread for aviation, was involved in the use of the Health and Usage Monitoring System (HUMS) and the integration of diagnostics technologies to monitor the condition of aircraft and detect system degradation and anomalies. The use of HUMS for developing CBM strategies and maintenance credits has been embraced by many in the U.S. and European countries. According to the Federal Aviation Administration (FAA) Advisory Circular (AC) 29-2C, Section MG-15, Airworthiness Approval of Rotorcraft Health and Usage Monitoring System for Installation, Maintenance Credit, and Instructions for Continued Airworthiness [2], hereby referred as HUMS AC, “Maintenance Credit” is defined as “to give approval to a HUMS application that adds to, replaces, or intervenes in industry accepted maintenance practices or flight operations”. “Maintenance Credit” and “CBM” used by FAA and DoD, respectively, are two different terms but give the same end result. For example, the Main Rotor Pitch Housing of the Apache helicopter is currently a safe-life designed component and has the retirement life of 1,193 hours. With the use of the CBM approach including usage monitoring, a conservative 50% extension in fatigue life could be given. Consequently, the replacement frequency of the Rotor Pitch Housing would be reduced. As a result, for a given fleet size, approximately 2,385 maintenance hours can be avoided [3]. The Army CBM approach and result fits perfectly in the FAA “Maintenance Credit” term.

CBM$^+$, which is now adopted by DoD, has been evolved from diagnostics to prognostics-diagnostics based CBM. In addition to operating processes and metrics, CBM$^+$ expands CBM to include related technologies supporting the predictive capabilities and the determination of the remaining useful life of Army systems. Specifically, CBM$^+$ include embedded and off-system sensors that record and monitor equipment operating parameters, portable maintenance aids with interactive electronic

technical manuals that facilitate troubleshooting and repair actions, and network communication equipment that enable remote analysis [4].

ARMY RESEARCH LABORATORY CBM$^+$ ENTERPRISE

The U.S. Army Research Laboratory (ARL) of the U.S. Army Research Development and Engineering Command (RDECOM) is the Army's corporate, or central, laboratory. Its diverse assortment of unique facilities and dedicated workforce of government and private sector partners make up the largest source of word-class integrated research and analysis in the Army. ARL is a part of the two-star RDECOM to which all the Research, Development, and Engineering Centers (RDECs) report. There are nine RDECs under RDECOM. They are Army Materials Systems Analysis Agency, Aviation and Missile RDEC, Armament RDEC, Army Research Laboratory, Communications and Electronics RDEC, Edgewood Chem-Bio Center, Natick Soldier Center, Simulation and Training Technology Center, and Tank and Automotive RDEC. Each RDEC is responsible for the research, development, and engineering associated with a specific type of Army asset, e.g., analysis, aviation, armament. ARL has six different directorates, which include Vehicle Technology, Human Research and Engineering, Survivability, Communication and Information Sciences, Sensors and Electron Devices, and Weapons and Materials Research Directorate. The ARL CBM$^+$ Enterprise is lead by the Vehicle Technology Directorate (VTD) but the coordination goes across ARL Directorates and even extends to other RDECs to support the Army Materials Command (AMC) CBM objectives. The AMC goals are to reduce the maintenance burden on the U.S. Army Soldiers and operational and support costs, increase operational readiness rates, and enhance safety,

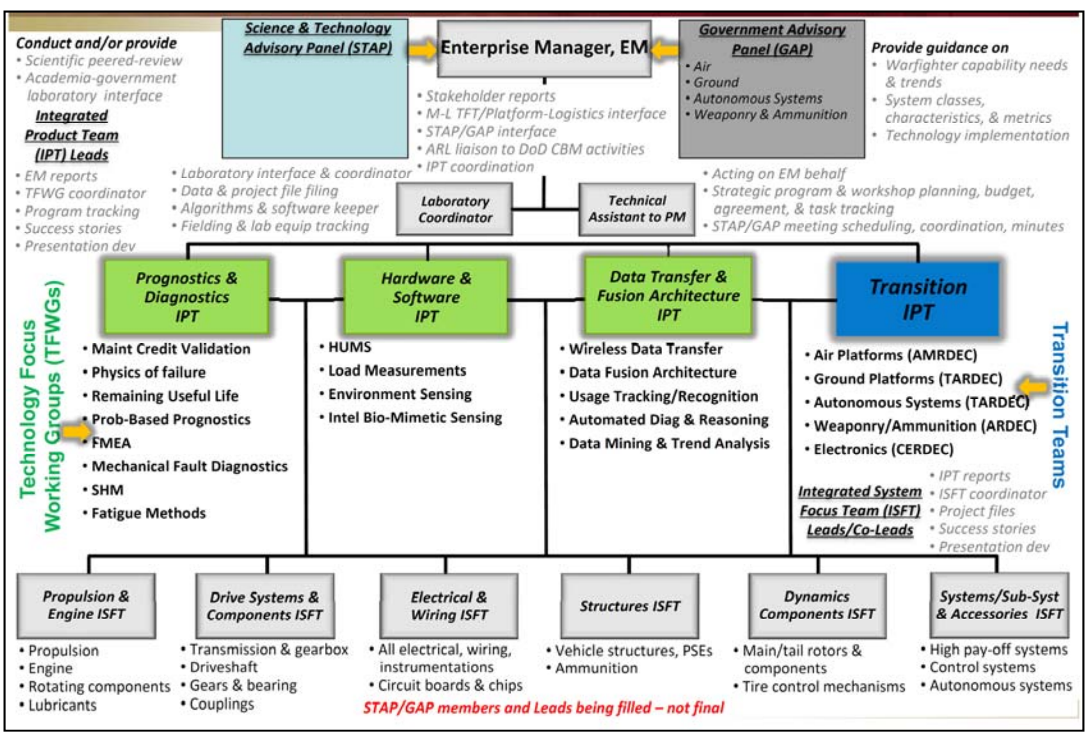

Figure 1: ARL CBM$^+$ Enterprise Structures and Strategies

CBM$^+$ ENTERPRISE STRUCTURES AND INTEGRATED PRODUCT TEAMS

ARL CBM$^+$ Enterprise, as depicted in Figure 1, is supported by two panels, e.g., Science and Technology (STAP) and Government Advisory Panel (GAP). STAP is consisted of members from academia and industry, whose roles are to conduct the annual scientific peered-review and provide academia-government laboratory interfaces. GAP is consisted of high-level Government members, whose roles are to provide guidance on Warfighter capability needs and trends, system classes, characteristics and metrics, and technology implementation strategies.

ARL CBM$^+$ Enterprise focuses on Prognostics and Diagnostics, Hardware and Software, Data Transfer and Fusion Architecture, and Transition. These research focuses are conducted by Integrated Product Teams (IPTs), which have researchers who reside across ARL Directorates as well as under other RDECs. Under each IPT focus, specific research areas are identified and investigated by the Technology Focus Working Groups (TFWGs), which are consisted of research members, again, who reside across ARL Directorates as well as under other RDECs. These identified technologies focuses aim at Army platforms including air, ground, and autonomous systems; weaponry and ammunition; and electronics components. Particularly, these technologies focus on propulsion and engine, drive system and component, electrical and wiring, structures, dynamics components, and system and/or sub-system and accessories. When a particular technology has been matured at an appropriate technology readiness level, it will be subjected to the technology demonstration and transition process. Applicable technologies, which have been successfully demonstrated, can eventually be introduced into Army platforms, systems, or sub-systems. The Transition IPT is consisted of members from RDECs including Aviation and Missile, Tank and Automobile, Armament, and Communications and Electronics.

MAINTENANCE CREDIT VALIDATION AND FORMULATION

The technology focus areas, identified in the CBM$^+$ Enterprise, cover a wide variety of research, in which results can provide matured technology insertions to a particularly platform, subsystem, or component. CBM$^+$ research results can also be used to establish processes to formulate or validate maintenance decision making and solution, which is supported by cross-cutting technologies. For CBM solutions or maintenance credits to be valid and accurate, a scientific process and systematic way of substantiating the proposed credit is needed to minimize the possibility of making a wrong decision. The FAA has developed a framework for the credit validation for rotorcraft applications as outlined in the HUMS AC. The maintenance credit validation process is an end-to-end system approach, which covers the qualification of on-board and ground-based equipment including sensors and software. The core validation process, as highlighted in Figure 2, explains the necessary steps to substantiate the proposed maintenance credit and to develop instructions for continued airworthiness (ICA) of HUMS. ICA also provides the direct evidence of the aircraft condition and generates more data for full validation when being in service.

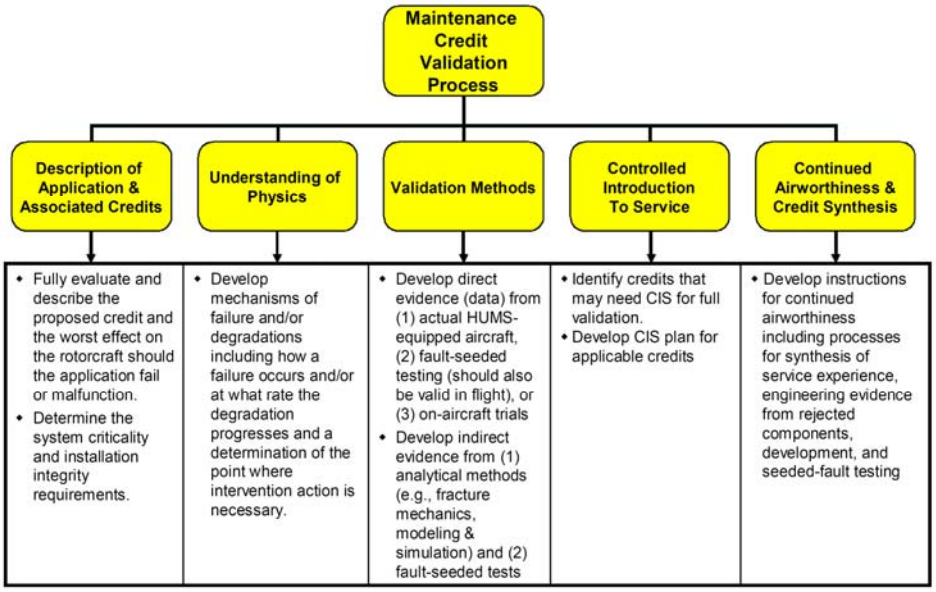

Figure 2: FAA Maintenance Credit Validation Process

Figure 3 highlights a framework for formulating the CBM action, e.g., usage credit, based on actual usage spectrum obtained from a HUMS. This approach is applicable to the rotorcraft safe-life components. Usage monitoring, using HUMS and Flight Regime Recognition algorithm, is conducted to record the rotorcraft actual usage spectrum. The collected usage spectrum then can be compared with the design one, which has been developed by the Original Engine Manufacturer (OEM) and typically consists of worse-case maneuvers, to determine the usage credit. The usage spectrum is comprised of many regimes or maneuvers, which, depending on the severity, can result in fatigue damage on critical components. Flight load surveys were done by EOM to determine the load distribution and the corresponding damage rate exerted on each component. From the comparison of actual usage to the worse-case usage spectrum, and with the use of damage rate of the surveyed component, actual fatigue damage accumulation and the remaining useful life of the monitored component can be determined.

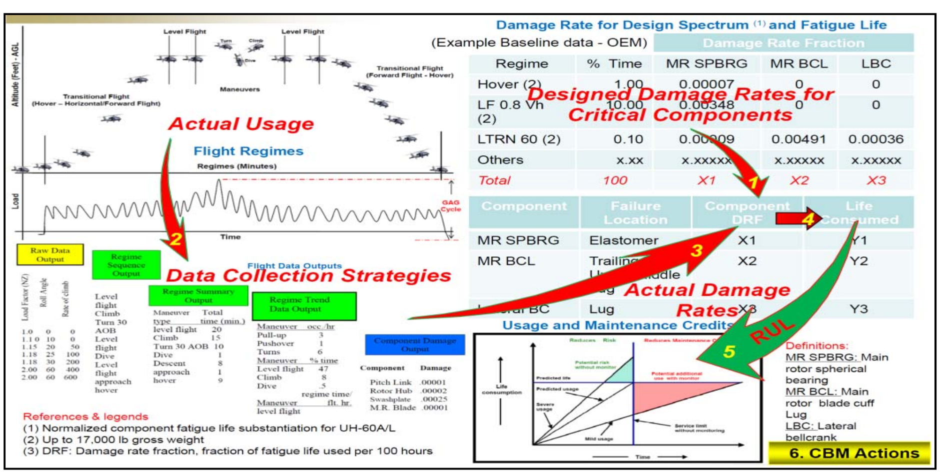

Figure 3: Framework of Usage-Based Maintenance Credit Formulation

The Tail Rotor Output Shat and Nut (TROSN) of a UH-60 Black Hawk helicopter, for example, can be used to demonstrate the formulated CBM action based on the usage monitoring. The TROSN component retirement life (CRT) was estimated to be 5,100 flight hours. Assuming the UH-60 Black Hawk helicopter has been in service and accrued 1,200 flight hours without usage monitoring. The TROSN fatigue damage fraction is 0.2353, e.g., 1,200 flight hours divided by the TROSN CRT, which is 5,100 flight hours. The selected component design damage rate per 100 flight hours (1) is 0.00196 given by OEM per reference [5] as seen in Table 1. To demonstrate the impact of different usage spectrum on the CBM decisions, Troop Transport (2) and Heavy Lift (3) missions are simulated. Additionally, it was assumed that after the selected component (TROSN) had been flown for 1,200 flight hours on a non-HUMS-equipped Black Hawk helicopter, a decision was made to install a HUMS on this helicopter.

No	Regime Description	1		2		3	
	Component: Tail Rotor Output Shat and Nut	*Time (%)*	*Design*	*Time (%)*	*TT*	*Time (%)*	*HL*
1	*Hover*	6.266		5.000	0.0000	16.800	0.0000
2	*Left sidewards flight*	0.500		0.500	0.0000	0.500	0.0000
3	*Right sidewards flighht*	0.500		0.500	0.0000	0.500	0.0000
4	*Rewards flight*	0.500		0.200	0.0000	0.200	0.0000
5	*Climb*	4.198		7.200	0.0000	5.000	0.0000
6	*Level flight at 0.4 Vh*	3.157					
7	*Level flight at 0.5 Vh*	3.157				60.000	0.0000
8	*Level flight at 0.6 Vh*	4.341					
9	*Level flight at 0.7 Vh*	4.736					
10	*Level flight at 0.8 Vh*	16.675		52.000	0.0000		
11	*Level flight at 0.9 Vh*	23.679					
12	*Level flight at 1.0 Vh*	11.839					
13	*Left sideslip*	0.500	0.0044			2.000	0.0176
14	*Right sideslip*	0.500	0.0044			2.000	0.0176
15	*Auto*	1.363					
16	*Part power descent*	2.500					
17	*Dive*	2.324	0.0039				
18	*Take off*	0.665		8.400	0.0000		
19	*Left hover turn*	0.550		1.000	0.0000	1.000	0.0000
20	*Right hover turn*	0.550		1.000	0.0000	1.000	0.0000
21	*Left turn 30 degree angle of bank*	4.166		4.000	0.0000	4.000	0.0000
22	*Right turn 30 degree angle of bank*	4.166		4.000	0.0000	4.000	0.0000
23	*Left turn 45 degree angle of bank*	0.665	0.0003	1.000	0.0005		
24	*Right turn 45 degree angle of bank*	0.665		1.000	0.0000		
25	*Left turn 60 degree angle of bank*	0.124	0.0006				
26	*Right turn 60 degree angle of bank*	0.124					
27	*Left turn during autorotation*	0.209					
28	*Right turn during autorotation*	0.209					
29	*Normal Landing*	0.264		9.600	0.0000	3.000	0.0000
30	*Running Landing*	0.098		4.000	0.0000		
31	*Rudder reversal - hover*	0.046					
32	*Rudder reversal - level flight*	0.122	0.0045				
33	*Longitudinal cyclic stick reversal - hover*	0.046					
34	*Longitudinal cyclic stick reversal - level flight*	0.122					
35	*Lateral cyclic stick reversal - hover*	0.046					
36	*Lateral cyclic stick reversal - level flight*	0.122	0.0013				
37	*Moderate pull-out (1.75g)*	0.278		0.600	0.0000		
38	*Severe pull-out (2.25g)*	0.025					
39	*Droop stop pounding*	0.000					
40	*Ground-air-ground load cycle per flight*	0.000	0.0002				
	TOTAL	**100**	**0.0196**	**100**	**0.0005**	**100**	**0.0352**

1 = Baseline Design Spectrum Flight Regimes
2 = Simulated Troop Transport (TT) Flight Regime Spectrum
3 = Simulated Heavy Lift (HL) Flight Regime Spectrum

Table 1: Example of Usage Spectrum and TROSN Fatigue Damage Rate Per 100 Hours

As shown in Figure 4, for the Troop Transport mission, at its CRT of 5,100 flight hours (Cx), only 28 percent (Cy) of the TROSN fatigue damage has been actually consumed. The remaining 72 percent is un-used fatigue life (UUFL). As a result, the usage credit for TROSN can be obtained to postpone the component replacement at a predetermined flight hours. As calculated, Figure 4, an additional flight time of 2,808 hours is proposed to fly the TROSN beyond its CRT with the safety factor of 2. Depending on the fleet size, this proposed usage credit, if approved and implemented, could reduce several thousand of maintenance hours, which, consequently, increase the aircraft availability and mission readiness.

On the other hand, if the same Black Hawk helicopter is used for the Heavy Lift mission, after 1,200 of un-monitored flight hours (Ax), a decision for the early removal of the TROSN component is recommended to prevent a potential catastrophic failure due to its severe usage. As shown in Figure 4, for the Heavy Lift mission, TROSN has a fatigue damage rate of 0.0352 per 100 hours. At 2,280 flight hours (Dx), the total fatigue damage of TROSN has been completely consumed. Continuing the mission beyond 2,280 flight hours is, therefore, not recommended. This CBM action, e.g., the early removal of TROSN, if approved and implemented, could avoid unscheduled replacement of the TROSN component due to its potential unexpected failure, if remained on wing until using up its CRT. As a result, this CBM action could reduce the unnecessary downtime of the Black Hawk helicopter and possibly protect its aircrew and Soldiers from injuries or fatalities. Avoiding these adverse potentials could result in the substantial reduction of costs in operating and sustaining Army vehicles and forces.

The formulation of CBM solutions, e.g., usage credit, can only be as good as the collected data and the incorporated technology such as the flight regime recognition algorithm. The task of validating the data collection, handing, and mining as well as

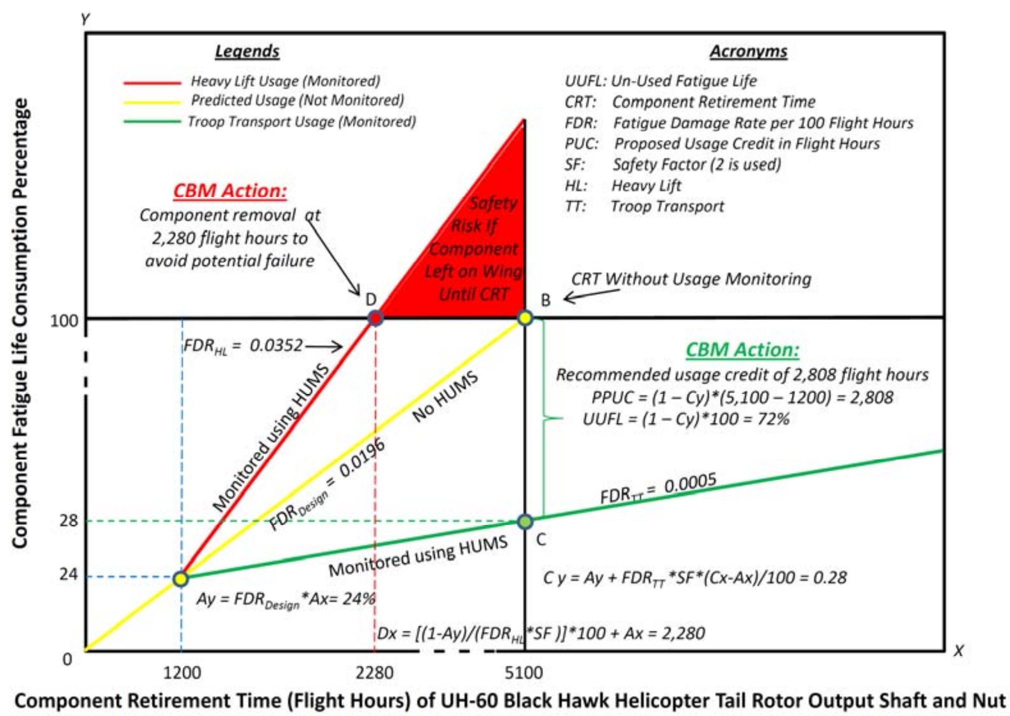

Figure 4: CBM Actions – Early Component Removal and Usage Credit

the accuracy of the flight regime recognition becomes one of critical steps in validating the CBM solution or maintenance credit at a high level of confidence. The validation becomes more complicated when HUMS is used to monitor the damage-tolerant designed structures or dynamics components.

CONCLUSION

ARL has developed the CBM^+ S&T Enterprise strategies to support the Army CBM^+ implementation goals and is developing a process to formulate and validate maintenance credits or maintenance-related decisions. One of the maintenance actions includes the establishment of usage credits. The CRT determination is based on the worse-case spectrum developed by OEM in accordance with the user's requirement and the intended mission. CBM actions can be established using HUMS to monitor the aircraft usage. Depending on the severity of the flight usage spectrum, usage credits for life-limited components can be formulated and approved for retaining the monitored component on wing beyond its CRT, or early removal of the monitored component may be scheduled even before having reached its CRT to prevent the potential failure due to the aircraft severe usage. Usage monitoring and resultant CBM actions, if approved and implemented, can effectively protect Soldiers from injuries or fatalities, reduce operation and sustainment costs, and increase the Army vehicle availability and forces.

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